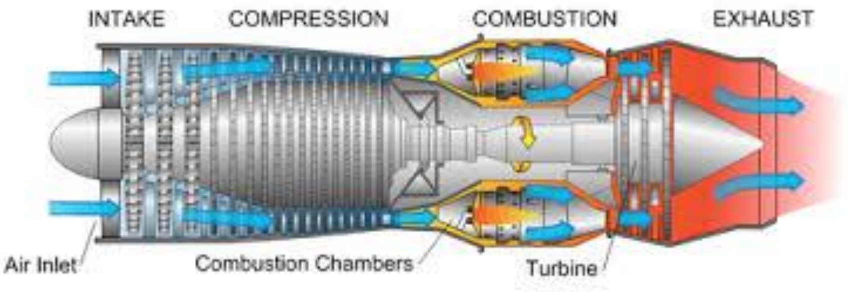
TIKRIT UNIVERSITY

COLLEGE OF ENGINEERING

MECHNICAL DEPARTMENT

INTERNAL COMBUSTION ENGINE



Chapter Two

Engine Design and Performance Parameters

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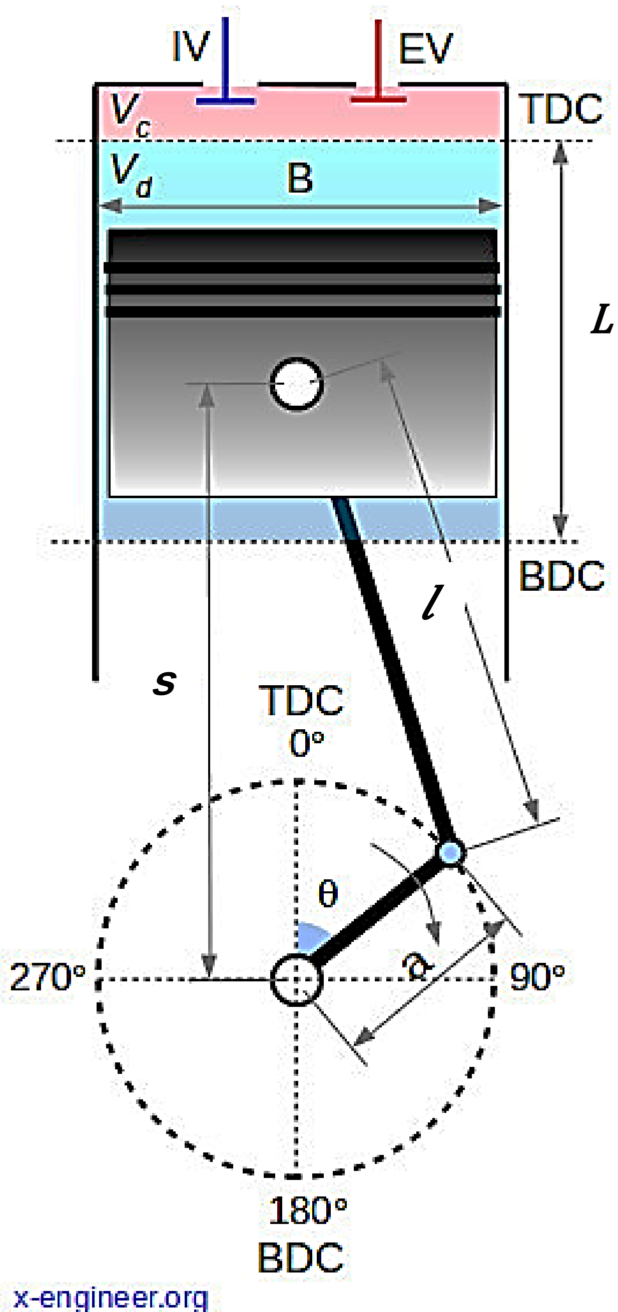
Engine Geometry:

The following parameters define the basic geometry of a reciprocating engine.



Relative location of piston center w.r.t. Crank Axis at any crank angle, $s(\theta)$ is given by:

$$s(\theta) = a\cos\theta + \left(l^2 - a^2\sin^2\theta\right)^{1/2}$$

Instantaneous surface area of the thermodynamic system, $A(\theta)$ is given by:

$$A(\theta) = A_{ch} + A_p + A_{wall}(\theta)$$

Cylinder volume when piston at TDC ($s=l+a$) defined as the **clearance volume** V_c

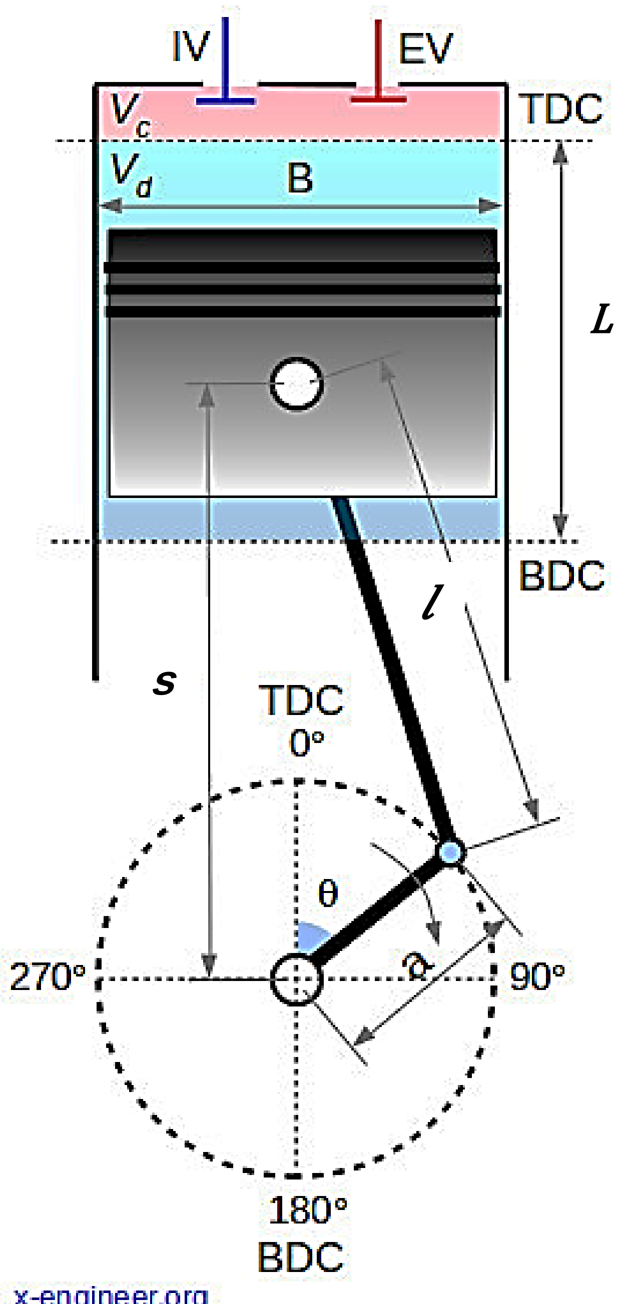
The cylinder volume at any crank angle $V(\theta)$ is:

$$V(\theta) = V_c + \frac{\pi B^2}{4}(l + a - s(\theta))$$

Maximum displacement, or swept, volume: $V_d = \frac{\pi B^2}{4} L$

Compression ratio: $r = \frac{V_{BC}}{V_{TC}} = \frac{V_c + V_d}{V_c}$

Engine Geometry



Cylinder Bore-to-Stroke Ratio:

$$R_{BS} = \frac{\text{Bore}}{\text{Stroke Length}} = \frac{B}{2a}$$

$R_{BS} = 0.8 - 1.2$ for small and medium size engines, decreases to about 0.5 for large low speed CI engines. However, for most engines B ~ L (square engine)

Kinematic Rod Ratio

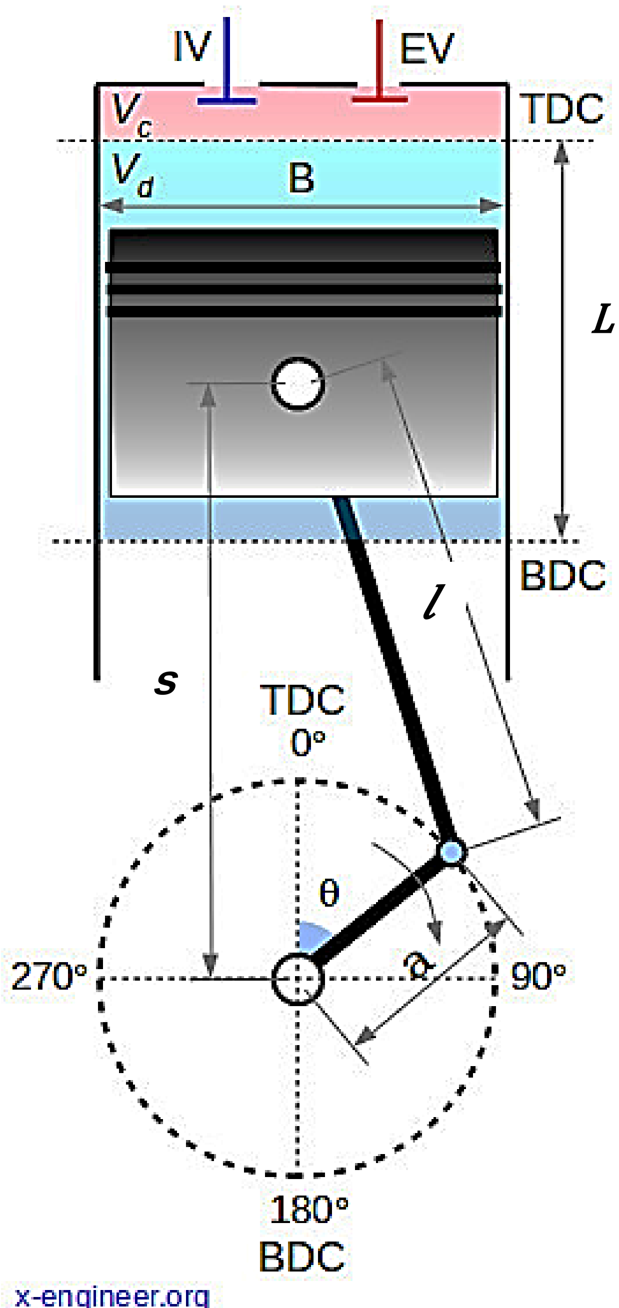
$$R_R = \frac{\text{Connecting Rod Length}}{\text{Crank Radius}} = \frac{l}{a}$$

$R_R = 3 - 4$ for small and medium size engines.

$R_R = 5 - 9$ for large low speed CI engines.

In engine design, L and a are related by: $L = 2a$

Mean and Instantaneous Piston Speeds



Let start with the relation of relative location of piston center w.r.t. Crank Axis at any crank angle:

$$s(\theta) = a\cos\theta + \left(l^2 - a^2\sin^2\theta\right)^{1/2}$$

Then, the **average** and **instantaneous** piston speeds are given by:

$$\bar{U}_p = 2LN \qquad U_p = \frac{ds}{dt}$$

$$\frac{U_p}{\bar{U}_p} = \frac{\pi}{2}\sin\theta\left[1 + \frac{\cos\theta}{\left((l/a)^2 - \sin^2\theta\right)^{1/2}}\right]$$

- Where N is the rotational speed of the crank shaft in units revolutions per second. Average piston speed for all engines will normally be in the range of 5 to 15 m/sec with large diesel engines on the low end and high performance automobile engines on the high end.

- Average piston speed for a standard auto engine is ~15 m/s. Ultimately limited by material strength. Therefore engines with large strokes run at lower speeds those with small strokes can run at higher speeds.

Performance Parameters

Engine performance: Effectiveness of delivering power from combustion of fuels.

Engine Performance parameters:

1) Power and efficiency
2) Brake mean effective pressure and torque
3) Specific power output
4) Volumetric efficiency
5) Fuel-air ratio
6) Specific fuel consumption
7) Thermal efficiency and heat balance
8) Exhaust smoke and other emissions
9) Specific weight

Relative importance of these parameters depends on particular application for example:

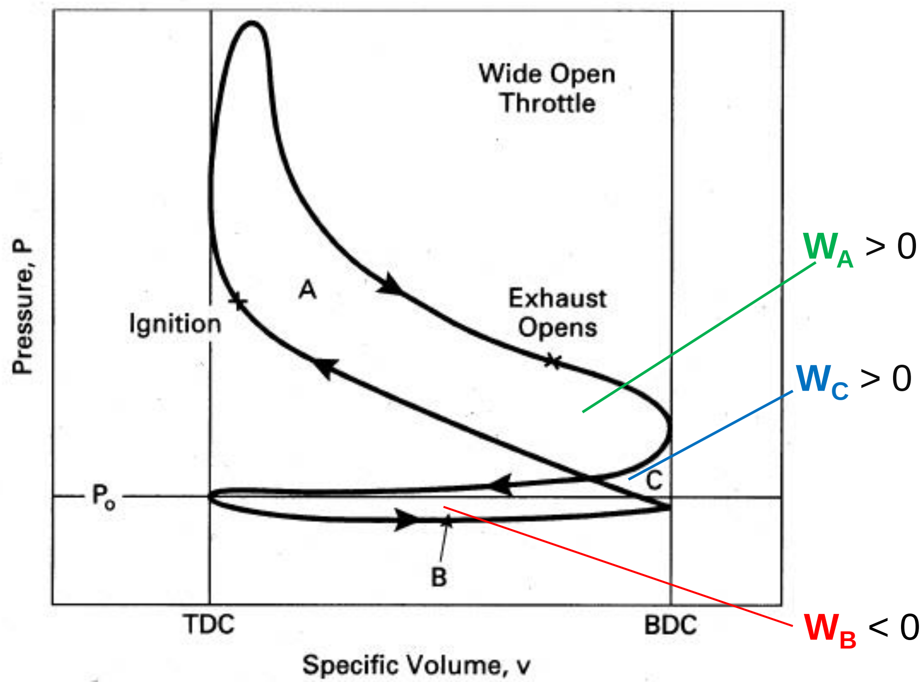
a) Aircraft engine: specific weight
b) Industrial engine: specific fuel consumption
c) Racing cars: specific power output

Indicated Work: is the work produced inside each engine cylinder as gas pressure pushes the piston downward during the expansion stroke.

Pressure data for the gas in the cylinder over the operating cycle of the engine can be used to calculate this work transfer from the gas to the piston.

The **indicated work per cycle** is:

$$W_i = \oint p\,dV$$



Gross indicated work per cycle: is the net work delivered to the piston over the compression and expansion strokes only:

$$W_{i,gross} = areaA + areaC = W_A + W_C$$

Pump work: is the net work delivered to the gas over the intake and exhaust strokes:

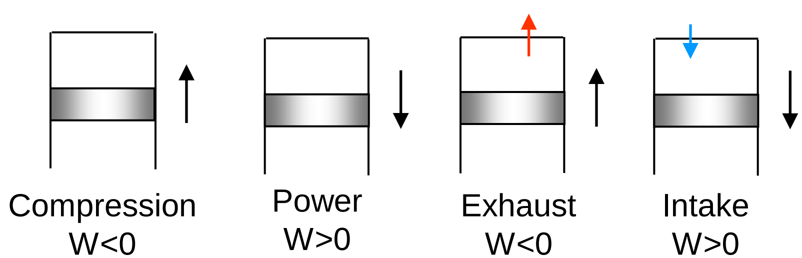
$$W_{pumping} = areaB + areaC = W_B + W_C$$

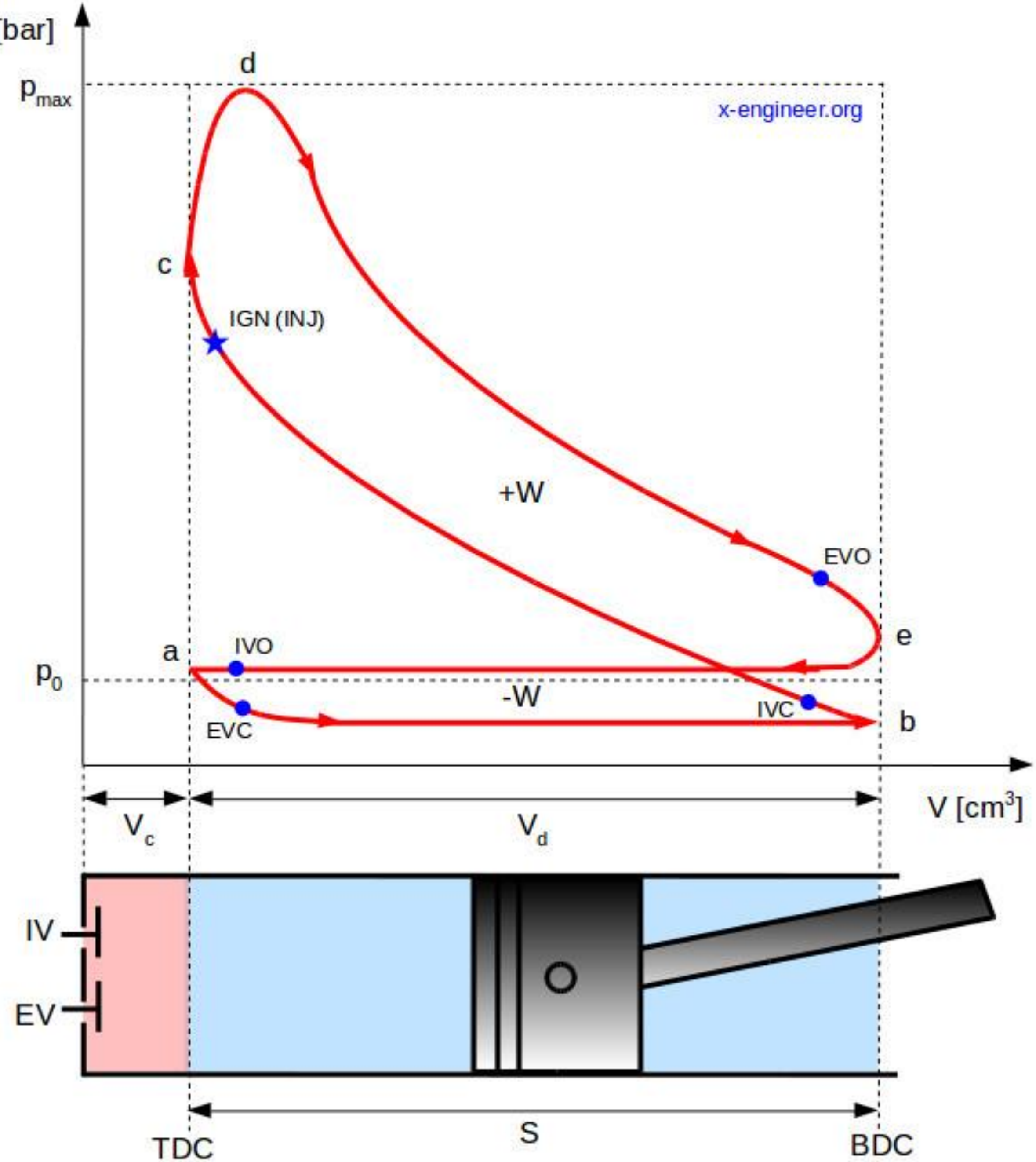
Net indicated work per cycle : work delivered over all strokes:

$$W_{i,net} = W_{i,gross} - W_{pumping}$$

$$W_{i,net} = (W_A + W_C) - (W_B + W_C)$$

$$W_{i,net} = W_A - W_B$$



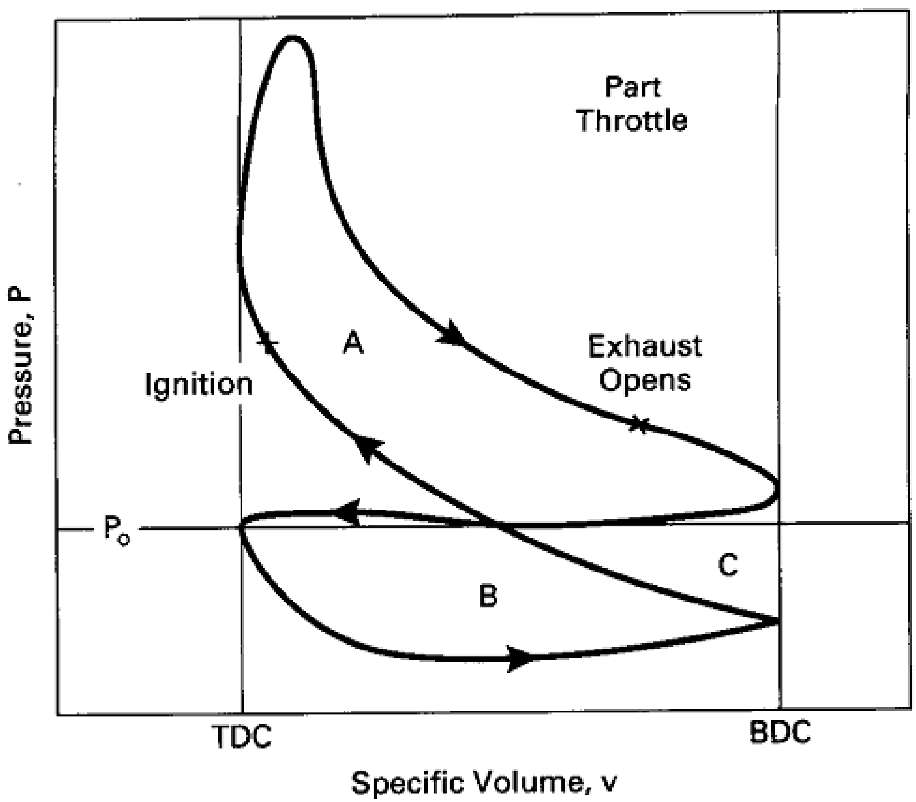


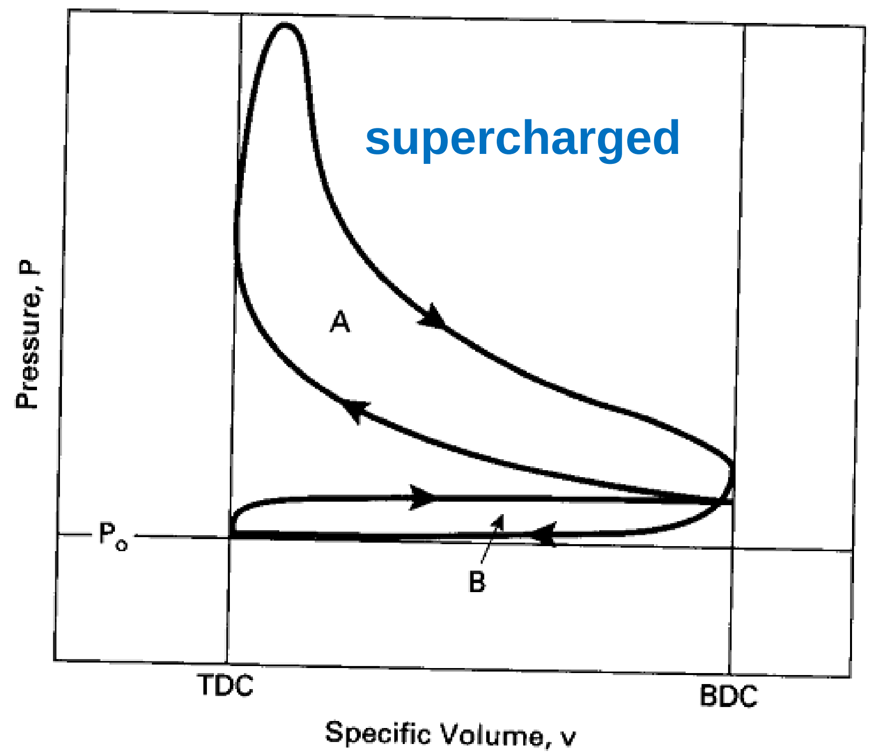
p [bar]
d
p_{max}
x-engineer.org
c
IGN (INJ)
+W
EVO
e
a
IVO
p_0
-W
IVC
b
EVC
V [cm^3]
V_c
V_d
IV
EV
S
TDC
BDC

INDICATED WORK AT PART LOAD & SUPERCHRGING

- At full load [wide open throttle (WOT)], the pressure at the intake valve is just below atmospheric pressure. However, at part load (part throttle) the pressure is much lower than atmospheric. Therefore, at part throttle the pump work (area B+C) can be significant compared to gross indicated work (area A+C).

- Engines with superchargers or turbochargers can have intake pressures greater than the exhaust pressure, giving a positive pump work. Supercharges increase the net indicated work but is a parasitic load since they are driven by the crankshaft.





Indicated Power

$P_i = W_i\, N / n_R$ Watt / units: (kJ/cycle) (rev/s) / (rev/cycle)

where N – crankshaft speed in rev/s; n_R – number of crank revolutions per cycle (= 2 for 4-stroke & = 1 for 2-stroke)

Power can be increased by increasing:
- the engine size, V_d
- compression ratio, r_c
- engine speed, N

Friction Power

Some of the power generated in the cylinder is used to overcome engine friction. The **friction power** is used to describe these losses:

$$P_f = P_i – P_b$$

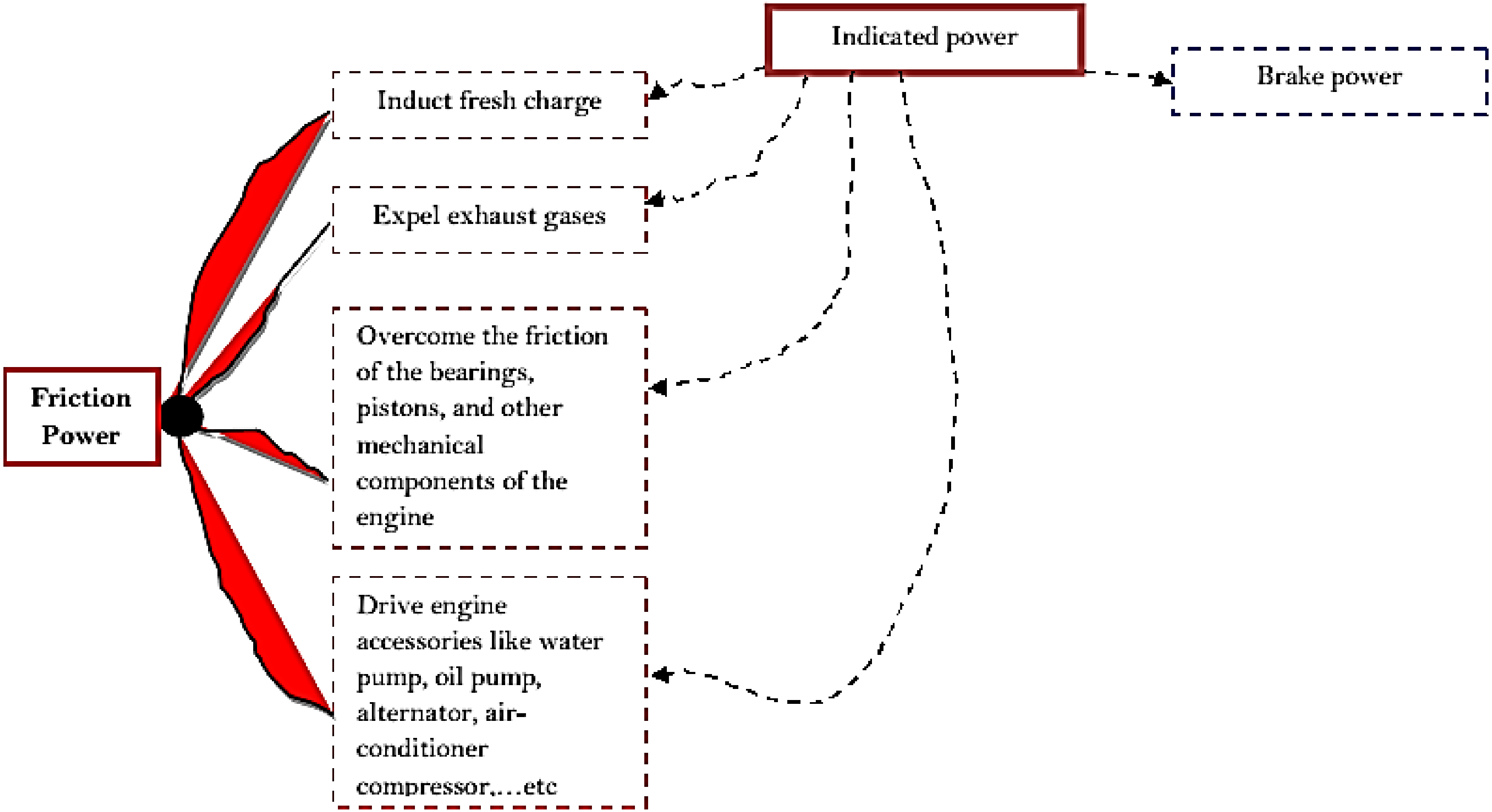
Friction power can be measured by motoring the engine.

Mechanical Efficiency

The mechanical efficiency is defined as:

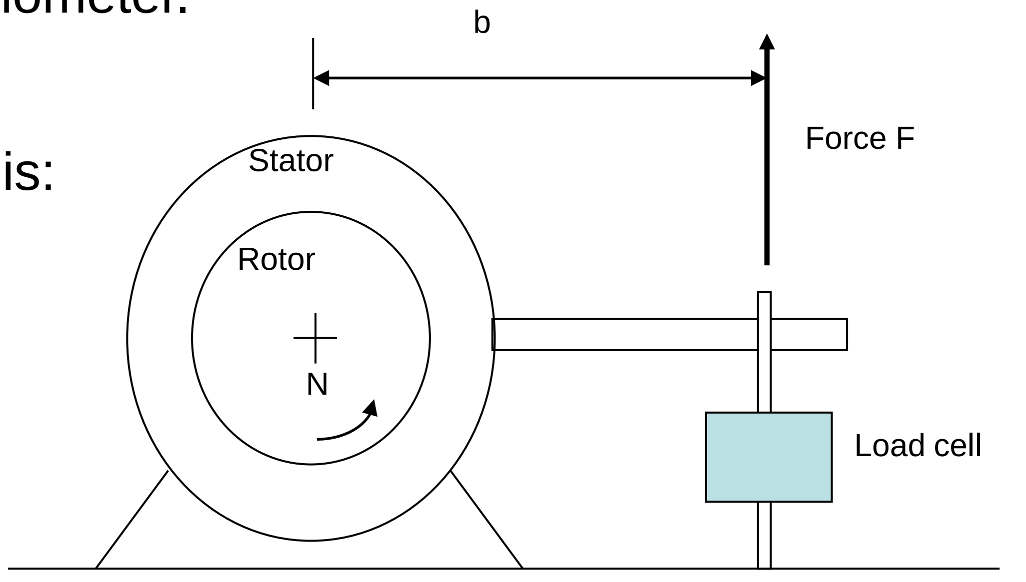
$$\eta_m = P_b / P_i = 1 - (P_f / P_i)$$

Mechanical efficiency depends on throttle position, engine design, and engine speed. Typical values for car engines at WOT are 90% @2000 RPM and 75% @ max speed.



Engine Torque and Brake Power

Torque is measured using a dynamometer.



The **torque** exerted by the engine is:

$$T = F \times b \quad \text{with units: } J$$

The **brake power** P_b delivered by the engine turning at a speed N and absorbed by the dynamometer is:

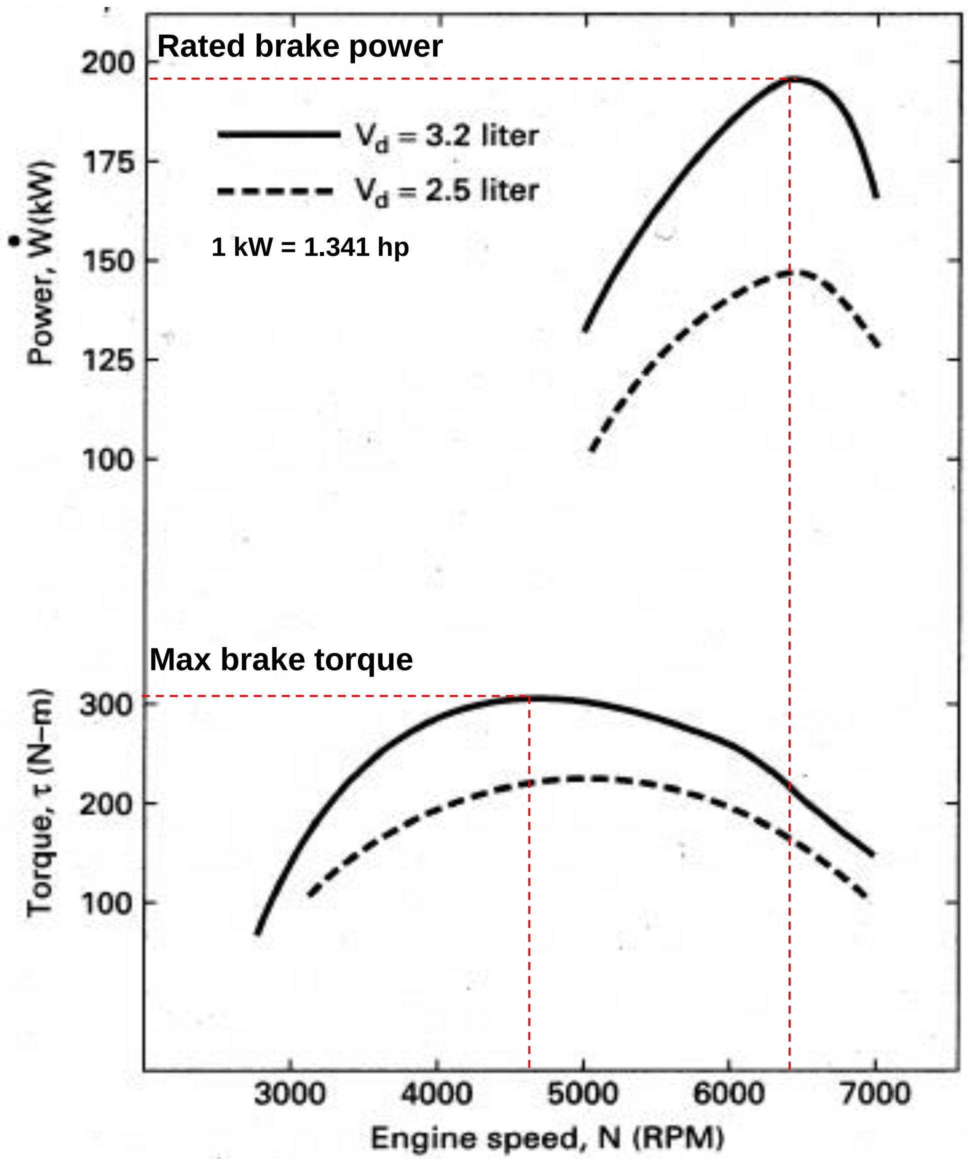
$$P_b = \omega\ T = (2\pi . N)\ T \quad W\ ;$$

units:

$$(rad/rev)(rev/s)(J) = Watt$$

Note: ω is the shaft angular velocity with units: rad/s

Power and Torque versus Engine Speed



There is a maximum in the brake power versus engine speed called the **rated brake power**.

At higher speeds brake power decreases as friction power becomes significant compared to the indicated power

There is a maximum in the torque versus speed called **maximum brake torque** (MBT).

Brake torque drops off:

- at lower speeds do to heat losses
- at higher speeds it becomes more difficult to ingest a full charge of air.

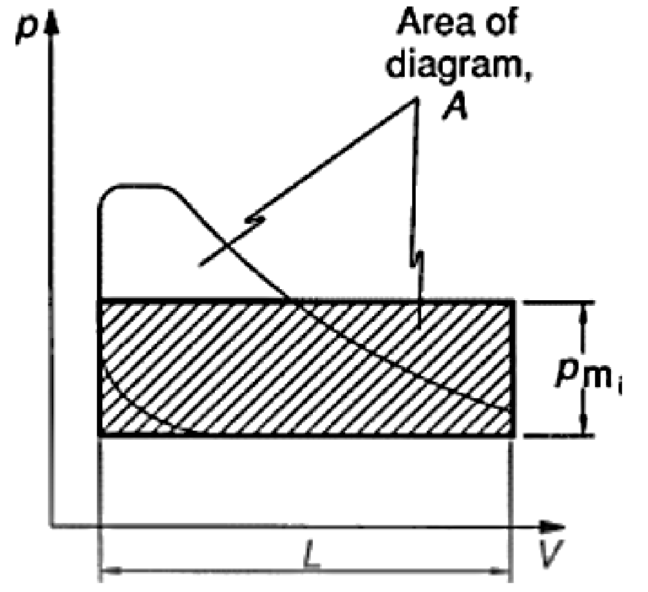
Indicated Mean Effective Pressure (IMEP)

imep is a fictitious *constant* pressure that would produce the same work per cycle if it acted on the piston during the power stroke.

$$imep = W_i / V_d = (P_i\, n_R) / (V_d\, N)$$

So: $P_i = imep\, V_d\, N / n_R$

$= imep\, A_p\, U_p / (2\, n_R)$



imep does not depend on engine speed, just like torque.

imep is a better parameter than torque to compare engines for design and output because it is independent of engine speed, N, and engine size, V_d.

Brake mean effective pressure (bmep) is defined as:

$$bmep = \frac{W_b}{V_d} = \frac{2\pi \cdot T \cdot n_R}{V_d} \quad \rightarrow \quad T = \frac{bmep \cdot V_d}{2\pi \cdot n_R}$$

Maximum BMEP

$$bmep = \frac{W_b}{V_d} = \frac{2\pi \cdot T \cdot n_R}{V_d}$$

- The maximum bmep is obtained at WOT at a particular engine speed
- Closing the throttle decreases the bmep
- For a given displacement, a higher maximum bmep means more torque
- For a given torque, a higher maximum bmep means smaller engine
- Higher maximum bmep means higher stresses and temperatures in the engine hence shorter engine life, or bulkier engine.
- For the same bmep 2-strokes have almost twice the power of 4-stroke

The maximum *BMEP* of four strokes good engine designs is well established:

SI engines: 800–1000 kPa*
CI engines: 500 –900 kPa

Turbocharged SI engines: 1200 –1700 kPa
Turbocharged CI engines: 1000 – 1400 kPa

*Values are at maximum brake torque at WOT
Note, at the rated (maximum) brake power the *BMEP* is 10 – 15% less

Specific Fuel Consumption

• For transportation vehicles fuel economy is generally given as:

mpg, or liters/100 km.

• In engine testing the fuel consumption is measured in terms of the fuel mass flow rate.

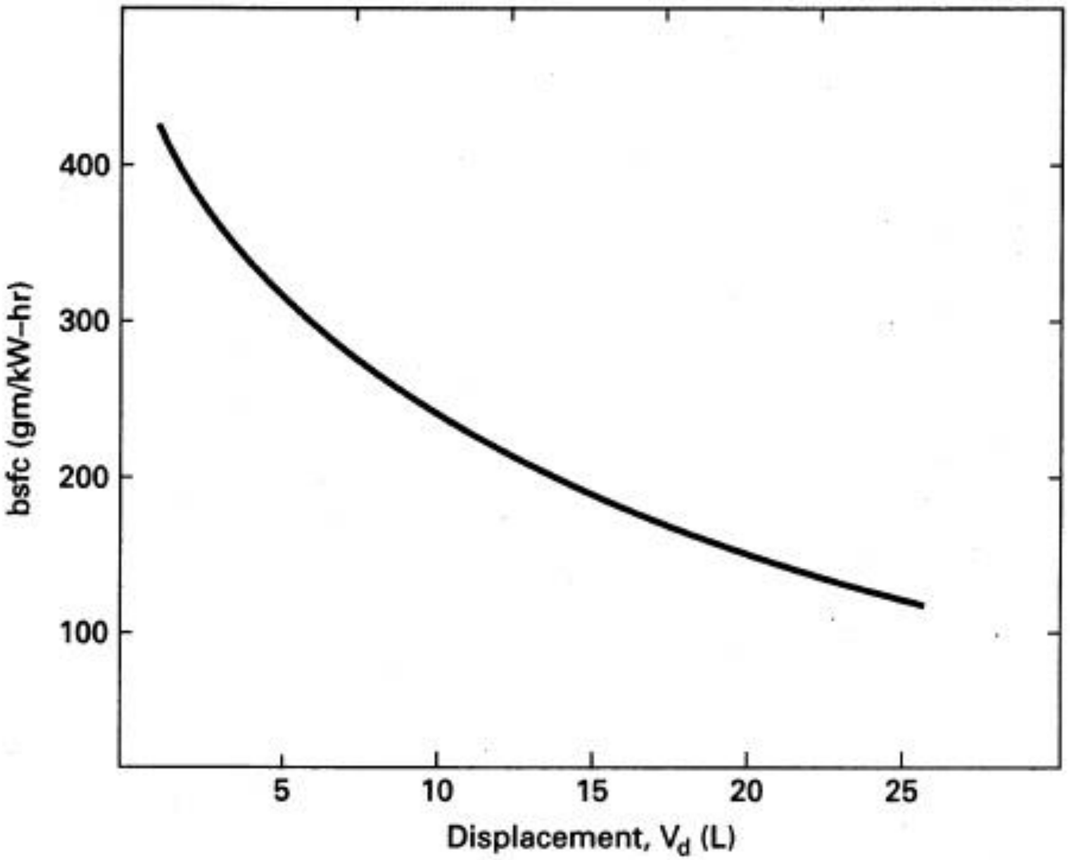
• The **specific fuel consumption, *sfc***, is a measure of how efficiently the fuel supplied to the engine is used to produce power,

$$bsfc = \dot{m}_f / P_b \qquad isfc = \dot{m}_f / P_i \quad \text{(w/units: g/kW-hr)}$$

• Clearly a low value for ***sfc*** is desirable since at a given power level less fuel will be consumed

Brake Specific Fuel Consumption vs Size

• BSFC decreases with engine size due to reduced heat losses from gas to cylinder wall.

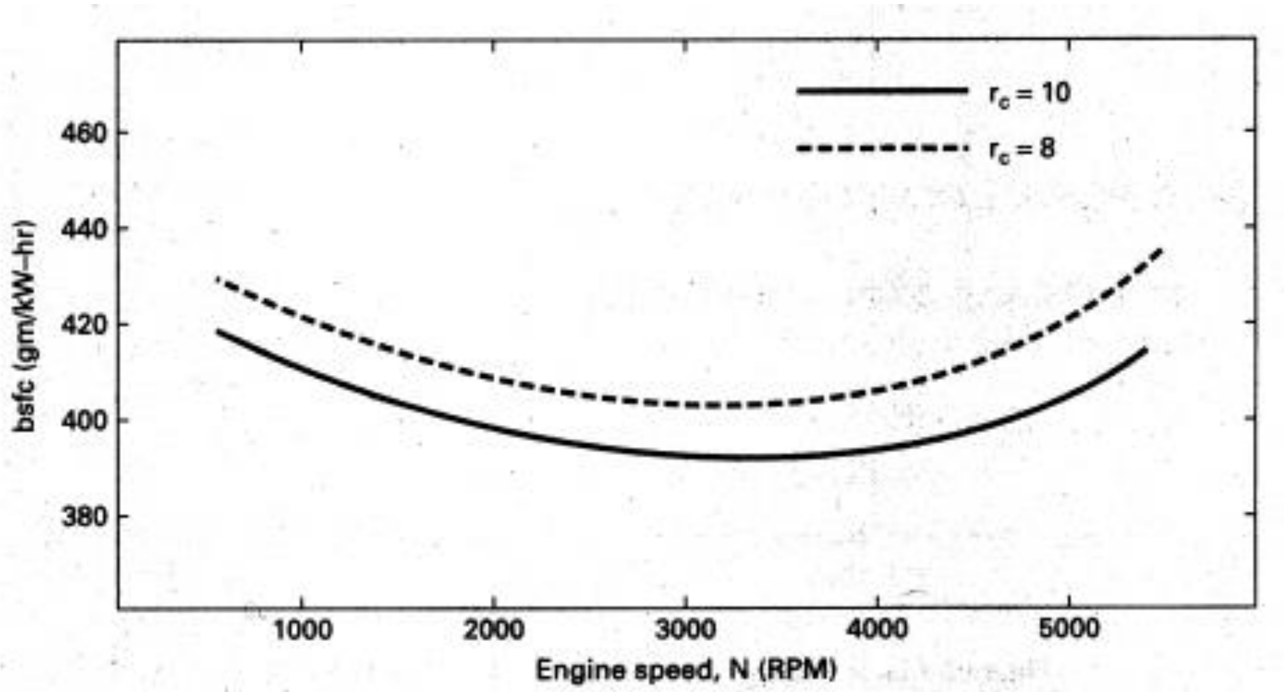


• Note: cylinder surface to volume ratio increases with bore diameter decreases.

$$\frac{cylinder\ surface\ area}{cylinder\ volume} = \frac{2\pi rL}{\pi r^2 L} \propto \frac{1}{r} \qquad r = B/2$$

Brake Specific Fuel Consumption vs Speed

- There is a minimum in the *bsfc* versus engine speed curve



- At high speeds the *bsfc* increases due to increased friction

•At lower speeds the *bsfc* increases due to increased time for heat losses from the gas to the cylinder and piston wall

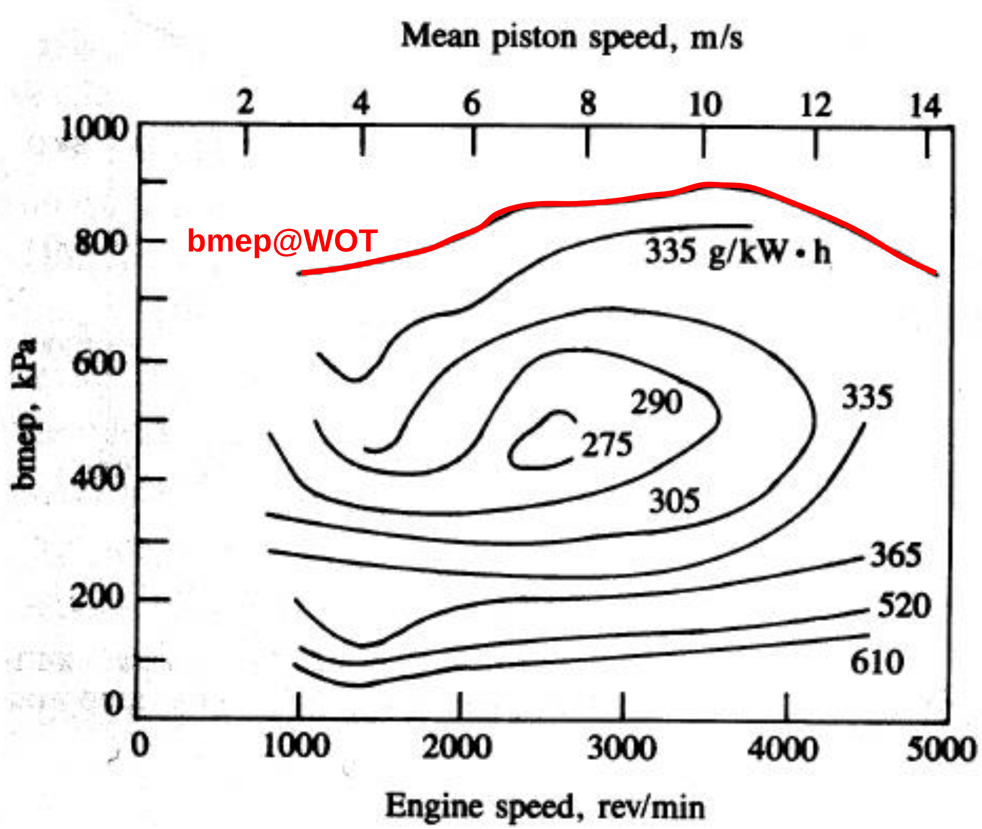
•*bsfc* increases with compression ratio due to higher thermal efficiency

Performance Maps

Performance map is used to display the *bsfc* over the engines full load and speed range.

Using a dynamometer to measure the torque and fuel mass flow rate you can calculate:

$$bmep = 2\pi \, T \, n_R \, / \, V_d \qquad P_b = 2\pi \, N \, T$$



$$bsfc = \dot{m}_f \, / \, P_b$$

Constant bsfc contours from a two-liter four cylinder SI engine

Engine Efficiencies

1. Combustion Efficiency

• The time for combustion in the cylinder is very short so not all the fuel may be consumed or local temperatures may not support combustion

• A small fraction of the fuel may not react and exits with the exhaust gas.

• The **combustion efficiency** is defined as actual heat input divided by theoretical heat input:

$$\eta_c = Q_{in} / (m_f \, Q_{HV}) = \dot{Q}_{in} / (\dot{m}_f \, Q_{HV})$$

Where Q_{in} = heat added by combustion per cycle
m_f = mass of fuel added to cylinder per cycle
Q_{HV} = heating value of the fuel (chemical energy per unit mass)

2. Thermal Efficiency

η_{th} = work per cycle / heat input per cycle

$$\eta_{th} = W / Q_{in} = W / (\eta_c\, m_f\, Q_{HV})$$

or in terms of rates…

η_{th} = power out/rate of heat input

$$\eta_{th} = \dot{P}/\dot{Q}_{in} = \dot{P}/(\eta_c\, \dot{m}_f\, Q_{HV})$$

- Thermal efficiencies can be given in terms of brake or indicated values

$$\eta_{th,b} = P_b/\dot{Q}_{in} = P_b/(\eta_c\, \dot{m}_f\, Q_{HV}) \qquad \eta_{th,i} = P_i/\dot{Q}_{in} = P_i/(\eta_c\, \dot{m}_f\, Q_{HV})$$

- Indicated thermal efficiencies are typically 50% to 60% and brake thermal efficiencies are usually about 30%

3. Arbitrary Overall Efficiency (or fuel conversion efficiency)

$$\eta_o = \dot{W}_b / (\dot{m}_f\, Q_{HV}) = P_b / (\dot{m}_f\, Q_{HV})$$

Note: η_o is very similar to η_{th}, the difference is that η_{th} takes into account only the actual fuel combusted in the engine.

Recall that:

$$bsfc = \dot{m}_f / P_b$$

Thus: $\eta_o = 1 / (sfc\, Q_{HV})$

4. Volumetric Efficiency

- Due to the short cycle time and flow restrictions less than ideal amount of air enters the cylinder.
- The effectiveness of an engine to induct air into the cylinders is measured by the volumetric efficiency which is the ratio of actual air inducted divided by the theoretical air inducted:

$$\eta_v = m_a / (\rho_a V_d) = n_R \dot{m}_a / (\rho_a V_d N)$$

where ρ_a is the density of air at atmospheric conditions P_o, T_o for an ideal gas $\rho_a = P_o / R_a T_o$ and $R_a = 0.287\ kJ/kg\text{-}K$ (at standard conditions $\rho_a = 1.181\ kg/m^3$)

- Typical values for WOT are in the range 75%-90%, and lower when the throttle is closed

Air-Fuel Ratio

- For combustion to take place, the proper ratio of air and fuel must be present in the cylinder.

- The **air-fuel ratio** is defined as:

$$AFR = m_a / m_f = \dot{m}_a / \dot{m}_f$$

- The ideal *AFR* is about 15:1, with homogenous combustion possible in the range of 6 to 19.

- For a SI engine the *AFR* is in the range of 12 to 18 depending on the operating conditions.

- For a CI engine, where the mixture is highly non-homogeneous and the *AFR* is in the range of 18 to 70.